PERMIAN BASIN PROVINCE (044)

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INTRODUCTION

The Permian Basin is one of the largest structural basins in North America. It encompasses a surface area in excess of 86,000 sq mi and includes all or parts of 52 counties located in West Texas and southeast New Mexico. Structurally, the Permian Basin is bounded on the south by the Marathon-Ouachita Fold Belt, on the west by the Diablo Platform and Pedernal Uplift, on the north by the Matador Arch, and on the east by the Eastern Shelf of the Permian (Midland) Basin and west flank of the Bend Arch. The basin is about 260 mi by 300 mi in area and is separated into eastern and western halves by a north-south trending Central Basin Platform. In cross section, the basin is an asymmetrical feature; the western half contains a thicker and more structurally deformed sequence of sedimentary rock. The Permian Basin has been characterized as a large structural depression formed as a result of downwarp in the Precambrian basement surface located at the southern margin of the North American craton. The basin was filled with Paleozoic and, to a much lesser extent, younger sediments. It acquired its present structural form by Early Permian time.

The overall basin is divisible into several distinct structural and tectonic elements. They are the Central Basin Platform and the Ozona Arch, which separate the Delaware and Val Verde Basins on the south and west from the Midland Basin on the north and east, the Northwestern Shelf on the southern extremity of the Pedernal Uplift and Matador Arch, and the Eastern Shelf on the western periphery of the Bend Arch. Stratigraphic sections of all systems of the Paleozoic are present and reach a maximum thickness in excess of 25,000 ft; however, complete vertical sequences of Paleozoic strata are rare. The Permian Basin, one of the most prolific petroleum provinces of North America, is now in a mature stage of exploration and development. Oil and gas have been found in rocks ranging from Cambrian to Cretaceous age; however, most hydrocarbons are found in rocks of Paleozoic age. Cumulative production in the province up to the end of 1990 was about 34.9 BBO, 90.7 TCFG, and 5.5 BBNGL.

Twelve confirmed conventional plays were defined and individually assessed for undiscovered oil and gas resources: Pre-Pennsylvanian, Delaware-Val Verde Basins (4401); Pre-Pennsylvanian, Central Basin Platform (4402); Pre-Pennsylvanian, Northwestern and Eastern Shelves (4403); Lower Pennsylvanian (Bend) Sandstone

(4404); Horseshoe Atoll, Upper Pennsylvanian - Wolfcampian (4405); Upper Pennsylvanian, Northwestern and Eastern Shelves, Northern Delaware and Midland Basins and Northern Central Basin Platform (4406); Upper Pennsylvanian and Lower Permian Slope and Basin Sandstones (4407); Wolfcampian Carbonate, Eastern and Southern Margins of the Central Basin Platform (4408); Spraberry-Dean (4409); San Andres-Clearfork, Central Basin Platform and Ozona Arch (4410); San Andres-Clearfork, Northwestern and Eastern Shelves (4411); and Delaware Sandstones (4412).

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CONVENTIONAL PLAYS

4401. PRE-PENNSYLVANIAN, DELAWARE-VAL VERDE BASINS PLAY

The definitive characteristics of this play are: (1) structural control of traps resulting from Late Paleozoic basement block faulting with some wrench displacement attending vertical movements; (2) Early Paleozoic reservoir rocks deposited in the interior of a carbonate shelf or platform setting (Tobosa Basin) with the play limited to the deep Delaware and Val Verde Basin settings and with reservoir quality enhanced by fracturing and dolomitization, (3) source rocks consisting primarily of Late Devonian Woodford Shale, and (4) dry-gas hydrocarbons resulting from the considerable depth and temperatures extant in the deep Delaware and Val Verde Basin settings. A significant detraction in the productivity of this play is dilution of hydrocarbon gases by carbon dioxide, which occupies as much as 50 percent of effective pore space in some reservoirs.

This gas play includes deep accumulations in structural and, to a lesser extent, structural-stratigraphic anticlinal traps in carbonate reservoirs of Lower Ordovician age. The play area is arcuate in shape, about 275 mi long and 70 mi at maximum width, and covers the Delaware and Val Verde Basins. It is bounded on the west and south by the Diablo Platform and the Marathon-Ouachita Fold Belt, and on the east by the Central Basin Platform and Ozona Arch. The thickness of Lower Paleozoic sedimentary rocks is less than 8,000 ft.

Reservoirs: Reservoir rocks are mainly crystalline cherty dolomite and limestone of Ordovician through Mississippian age, which have solution and vuggy porosity and are fractured and faulted. Lower Paleozoic rocks were deposited in a shallow-marine environment in the gently subsiding ancestral Tobosa Basin, which covered all of the province including the surrounding shelves. Carbonate reservoirs are in the Lower Ordovician Ellenburger Formation, the Upper Ordovician Montoya Formation, and the Silurian Fusselman Formation. Clastic reservoirs occur in the Ordovician Simpson Group. Fractures and joints in the carbonate rocks form adequate porosity and permeability conduits for migration of gas. Individual reservoir thicknesses are in excess of 500 ft. Drilling depths range from 8,400 to 24,000 ft.

Source rocks: Chief sources of hydrocarbons in the two basins may be: (1) Middle Ordovician shale and limestone; (2) Upper Devonian and Mississippian shale and shaly limestone (Woodford Shale); and (3) Pennsylvanian and Permian basinal shale facies. Major hydrocarbon generation probably occurred in Permian time. Generated

hydrocarbons migrated, probably long distances, into porous fractures and joints in lower Paleozoic carbonates.

Timing and migration: Structures controlling traps for this play were created during the Pennsylvanian. Traps are generally sealed by Pennsylvanian shales. Judging from known overburden thicknesses, and assuming present geothermal gradients (1-2¡ F/100 ft) are representative of those extant in the geologic past, oil should have been available for migration from the Late Devonian Woodford Shale into Lower Paleozoic traps during Late Permian time. The fact that hydrocarbons produced from these traps are exclusively dry gas indicates either that initial oil in these traps was displaced by later migration of gas or that early oil was cracked in place to produce the gas that is now present. A combination of these two processes may explain the extensive dry-gas concentrations that characterize this play. Dry-gas migration into these traps probably continues during the present day.

Traps: Trapping mechanisms are structural, primarily faulted, fractured, and jointed anticlinal features. Seals are overlying impermeable shale.

Exploration status: This play's cumulative production through 1990 consisted of 1.7 MMBO, 21.6 TCFG, and 97 MMBNGL. Gomez, the largest gas field, discovered in 1963, has produced 5.3 TCFG. The first discovery in the play occurred at Puckett in 1952 and has produced 2.9 TCFG. Most major discoveries were made in the 1950's and 1960's.

Resource potential: The broad expanse of unexplored area in the Ordovician Ellenburger Formation in this play indicates considerable potential for discovery of additional gas.

4402. PRE-PENNSYLVANIAN, CENTRAL BASIN PLATFORM PLAY

The definitive characteristics of this play are: (1) structural control of traps resulting from Late Paleozoic basement block faulting; (2) Early Paleozoic reservoir rocks deposited in the interior of an extensive carbonate or platform setting (Tobosa Basin) with the play limited to the crest of the Central Basin Platform and western portion of the Midland Basin and with reservoir quality enhanced by dolomitization, fractures, and Late Paleozoic karstification, and (3) source rocks consisting primarily of Late Devonian Woodford Shale and organic-rich Pennsylvanian and Permian shales in the adjacent Delaware, Val Verde, and Midland Basins. A principal limitation on potential productivity of this play is that it has been drilled extensively.

The play includes oil and subordinate gas accumulations in combined structural-stratigraphic traps and highly faulted structural traps below a major unconformity in reservoir rocks of primarily Lower Ordovician to Devonian age and secondarily of Pennsylvanian age. The play area is about 210 mi long by 80 mi wide, covering the Central Basin Platform, the western part of the Midland Basin, and the Ozona Arch. It is bounded on the west and south by the Delaware and Val Verde Basins and on the east by the Eastern Shelf. The thickness of lower Paleozoic sedimentary rocks is less than 7,500 ft.

Reservoirs: Reservoir rocks consist of Ordovician to Mississippian weathered carbonate, chert, and sandstone located below the major unconformity. Lower Paleozoic rocks were deposited in the ancestral Tobosa Basin under various environmental settings ranging from shallow open shelf, ramp, and deep basin to restricted shallow-water platform. Principal reservoirs are Devonian in age; reservoirs also occur in the Ordovician Ellenburger Formation, Simpson Group, Montoya Formation, Silurian Fusselman Formation, and Pennsylvanian Strawn Formation. Individual thicknesses of Devonian reservoirs are generally less than 150 ft. Porosities average 10 percent and permeabilities 55 mD. Drilling depths vary from 4,000 to 15,500 ft.

Source rocks: Associated organic-rich beds in the Devonian-Mississippian Woodford Shale are prolific source rocks. Hydrocarbon generation from this unit probably began during Pennsylvanian time. Generated hydrocarbons were trapped below the unconformity and migrated into nearby weathered reservoir rocks.

Timing and migration: The majority of structures responsible for trapping the oil and gas of this play were formed during Pennsylvanian time. Seals consist of shales deposited during the same period. The great quantity and mix of hydrocarbons in this play probably results from fluid migrating upward into traps on the Central Basin Platform from the adjacent Delaware, Val Verde, and Midland Basins during and after the Late Permian.

Traps: Trapping is by a combination of both structural and stratigraphic mechanisms. Structural traps are anticlines, fault blocks, and domes. Stratigraphic traps, prevalent on the Central Basin Platform, are pinch-out and eroded updip truncation types controlled by facies changes. Seals are provided by the Woodford Shale, and in impervious Upper Pennsylvanian carbonate strata and Lower Permian shale and carbonate, updip pinch-out and facies change permeability barriers. Trapped

hydrocarbons occur at depths ranging from 4,500 to 12,000 ft, with an average depth of about 9,500 ft.

Exploration status: This play's cumulative production through 1990 was of 3.1 BBO, 9.2 TCFG, and 906 MMBNGL. Block 31E, discovered in 1945, is the largest oil field and has produced 240 MMBO. The South Sand Belt is the largest gas field and has produced 1.7 TCFG since its discovery in 1955. The first discovery in the play was made in 1928 and most of the major discoveries were made during the 1940's and 1950's.

Resource potential: Potential for additional discoveries in this play is limited by extensive previous drilling.

4403. PRE-PENNSYLVANIAN, NORTHWESTERN AND EASTERN SHELVES PLAY

The definitive characteristics of this play are: (1) structural control of traps resulting from Late Paleozoic basement block faulting, (2) Early Paleozoic reservoir rocks deposited in the interior of an extensive carbonate shelf or platform setting (Tobosa Basin) with the play limited to the Northwestern and Eastern Shelf setting and reservoir quality enhanced by dolomitization, fracturing, and karstification, and (3) source rocks consisting of the Late Devonian Woodford Shale and organic rich Pennsylvanian and Permian shales in adjacent basinal settings. Future prospects of this play are limited by the extensive drilling to which it has been subjected.

The play includes oil and associated gas accumulations in structural-stratigraphic, structural, and, to a lesser extent, stratigraphic traps in carbonate and subordinate clastic reservoirs of Lower Mississippian through Cambrian age. The play area is triangular in shape and covers a large part of the province. It encompasses most of the Eastern Shelf, the northern part of the Midland Basin, and a large part of the Northwestern Shelf. The sides of this triangular area are about 235 mi and 220 mi in length. The thickness of lower Paleozoic sedimentary rocks is less than 5,000 ft.

Reservoirs: Reservoir rocks consist of Ordovician to Mississippian limestone and dolomite, together with a few Ordovician sandstone beds. Interbedded limestone and dolomite were deposited in the ancestral Tobosa Basin on platform, strandline, and deeper environments associated with evaporitic tidal-flat sabkha facies. Other reservoirs are mudstone, algal boundstone, wackestone, and oolitic grainstone. The most significant reservoirs are in the Ordovician Ellenburger Formation, Simpson Group, Montoya Formation, Silurian Fusselman and Upper Silurian Shale Formations, and other Devonian and Mississippian carbonate rocks. Individual reservoir

thicknesses are generally less than 100 ft; porosities average 8 percent and permeabilities 60 mD, the latter being extremely variable. Drilling depths vary from 5,800 to 13,600 ft.

Source rocks: Source rocks in the lower Paleozoic are considered to be indigenous organic-rich shale, argillaceous limestone, and mudstone. However, a large portion of the generated hydrocarbons may have migrated considerable distances along extensive fault and fracture systems from overlying and underlying source beds. Source rocks for hydrocarbons in Ordovician-Mississippian reservoirs are considered to be primarily the Woodford Shale. Hydrocarbon generation in lower Paleozoic source rocks probably occurred during Permian time, with Thermally mature hydrocarbons readily migrating into adjacent reservoirs.

Timing and migration: The structures, reservoirs, and seals forming the traps of this play were extant by the end of the Pennsylvanian Period. Oil was thermally mature and available for migration during Late Permian time. Subsequently, gas also followed the migration routes from the deep-basin source-rich locations up and onto the bordering platform areas. The greater concentration of hydrocarbons on the basinward margins of the shelf areas is consistent with the migration path inferred here.

Traps: Trapping is by a combination of structural and stratigraphic mechanisms. Simple and faulted anticlines exist, together with stratigraphic updip pinch-out, reservoir truncation, porosity barriers, and lateral facies changes. Interbedded shale, impervious crystalline and argillaceous carbonate, updip pinch-out, truncation, facies changes, and permeability barriers act as effective seals. Depths to trapped hydrocarbons are variable and range from 5,000 to 13,000 ft depending on the location within the play.

Exploration status: This play's cumulative production through 1990 was 965 MMBO, 1.1 TCFG, and 97 MMBNGL. Denton, discovered in 1949, is the largest oil field and has produced 102 MMBO. Benedum, discovered in 1947, is the largest gas field and has produced 191 BCFG. The first discovery in the play occurred in 1941, and most of the major discoveries were made prior to 1960.

Resource potential: Potential for new discoveries in this play is limited by extensive prior drilling.

4404. LOWER PENNSYLVANIAN (BEND) SANDSTONE PLAY

The definitive characteristics of this play are the Bend (Morrow-Atokan) age of the reservoirs and the location of reservoirs predominantly in the Delaware and Midland Basin settings. An encouraging aspect of this play is the success being experienced in the exploration for Morrow Sandstone gas reservoirs in the northern Delaware Basin and adjacent shelf area of New Mexico. A principal factor limiting exploration potential for the play is the commonplace complaint for the Permian Basin Province; that is, the extensive drilling and exploration history.

The play includes gas and minor oil accumulations in stratigraphic and structural traps associated with predominantly Early Pennsylvanian (Morrowan and Atokan Series) quartz sandstone and conglomerate reservoirs. These units were derived from highlands uplifted during the late Paleozoic collision of the ancestral North America plate with South America and Africa. This collision gave rise to the present configurations of the Permian Basin and the Ouachita structural front. The play limit on the north is the Palo Duro Basin. On the east, the play boundary is the province boundary. The pinch-out of reservoir facies on the Pedernal Uplift limits the play on the west. On the south, the play is limited by the frontal zone of the Ouachita Fold Belt. Maximum thickness of clastic wedges in this section exceeds 5,000 ft.

Reservoirs: Reservoirs in this play are predominantly quartz sandstones generally interpreted to have been deposited in deep water as turbidites. Some carbonate reservoirs exist and include both platform (Chapman) and deeper water detrital deposits (Rojo Caballos). Porosities range from 4-17 percent with an average value of 10-12 percent for both types of reservoirs. Permeabilities are measured in a range from single digits to a few tens of millidarcies. Average reservoir thicknesses are measured in the tens of ft. The overall Bend interval is measured in hundreds of feet. The productive depth range for this play is 5,500 to 12,000 ft.

Source rocks: Source rocks probably include the Late Devonian Woodford Shale and organic-rich Pennsylvanian shales in the Delaware and Midland Basins. The concentration of Morrow gas fields in the northern Delaware Basin and on the adjacent New Mexico shelf area is consistent with the possibility that gaseous hydrocarbons are migrating upward from the Delaware Basin.

Timing and migration: The combined structural and stratigraphic traps of this play were in existence during Pennsylvanian time. The preponderance of gas characterizing

the play may well result from leakage of gas upward from deeper early Paleozoic reservoirs in basinal settings. This style of migration probably continues at the present time.

Traps: Traps consist of simple anticlines, fault-bounded anticlines, and stratigraphic traps with both facies controlled and truncation pinch-outs. Shale beds in the section provide numerous seals.

Exploration status: Cumulative production for this play through 1990 was 141 MMBO, 5.7 TCFG, and 85 MMBNGL. Boyd, discovered in 1951, is the largest oil field, having produced 27 MMBO. Carlsbad South, discovered in 1968, is the largest gas field, with a production of 305 BCFG. The first oil was discovered in 1950 and the first gas in 1953. Major oil discoveries occurred prior to the 1970's. Major gas discoveries have continued into the 1980's.

Resource potential: This play has favorable potential for additional gas resources.

4405. HORSESHOE ATOLL, UPPER PENNSYLVANIAN-WOLFCAMPIAN PLAY

The definitive characteristics of this play are: (1) structural relief resulting from depositional-constructional upbuilding of a Late Paleozoic carbonate platform edge modified by erosion in step with regional subsidence, (2) reservoir rock consisting of carbonate platform-edge facies of Pennsylvanian Strawn through Permian Wolfcampian ages, and (3) source rocks probably consisting of Late Devonian Woodford Shale and organic-rich Pennsylvanian and Permian shales in the adjacent and subjacent Midland Basin. The relatively limited area and considerable drilling history of this play limit its prospective potential.

The play includes oil and associated gas accumulations trapped in stacked carbonate beds, and growth reef and organic-rich carbonate mound reservoirs of a massive reef bank of Pennsylvanian to Lower Permian age. As its name implies, the play area is an arcuate, horseshoe-shaped reefal platform edge about 150 mi long and 20-25 mi wide located in the northwestern part of the Eastern Shelf and the northern part of the Midland Basin. Maximum thickness of the reef complex is about 3,000 ft; it is buried to a depth of less than 10,000 ft.

Reservoirs: Reservoir rocks consist of porous grainstone, algal-mound wackestone, and boundstone contained within stacked, massive limestone and dolomitic limestone beds. Carbonate rocks in the massive reef consist of numerous fossil organisms including shell debris, algal, sponge, bryozoan, and crinoidal growths. Reservoirs are contained

in the Pennsylvanian Strawn, Canyon, and Cisco Formations. Cumulative reservoir thicknesses may range up to 1,500 ft, and porosities average 9 percent, and permeabilities average 28 mD. Drilling depths vary from 6,000 to 10,600 ft.

Source rocks: Source rocks for the Pennsylvanian reef reservoirs are adjacent organic-rich shale and shaly limestone deposited in the sediment-starved Midland Basin. Hydrocarbon generation in these organic-rich shale and shaly limestone beds probably occurred during Upper Permian time, with the hydrocarbons readily migrating into porous atoll limestones. Trapping mechanisms are stacked reefoidal carbonates, stratigraphic reef growth features, and associated organic-rich carbonate rocks. Seals consist of thick sequences of impervious mudstone and shale that surround and cover the former reef. Trapped hydrocarbons occur at depths of 5,000–10,000 ft and average about 7,400 ft.

Timing and migration: The reefal depositional structure forming the trapping configuration for this play was in place by early Permian time. Younger Permian shales seal the trap and it seems likely that organic-rich shales in the thick Midland Basin sequence toward the south were supplying hydrocarbons to the trap beginning at least by late Permian time.

Traps: The trapping mechanism for this play consists of upward growth of carbonate platform-edge facies in step with regional subsidence to form a depositional reef, 1,500 ft thick, with the plan configuration of a large atoll.

Exploration status: This play's cumulative production through 1990 was of 2.7 BBO, 1.9 TCFG, and 557 MMBNGL. Scurry, the largest oil field, was the play's first discovery in 1948 and has produced 1.6 BBO. The major discoveries in the play occurred during the 1940's and 1950's.

Resource potential: Potential for additional discoveries in this play is limited by extensive earlier drilling.

4406. UPPER PENNSYLVANIAN, NORTHWESTERN AND EASTERN SHELVES, NORTHERN DELAWARE AND MIDLAND BASINS, AND NORTHERN CENTRAL BASIN PLATFORM PLAY

The definitive characteristics of this play are the Late Pennsylvanian age of its reservoirs, the preponderance of a carbonate reservoir lithology, and the importance of oil fields over gas fields in the play's production. A major factor limiting the exploration potential of this play is extensive previous drilling.

The play includes oil and subordinate gas fields in stratigraphic and structural traps in shelf sequence carbonates and, to a lesser extent, clastic reservoirs of Late Pennsylvanian age. The play covers the Northwestern and Eastern Shelf, and is bounded on the east by the province boundary, on the west by the Pedernal Uplift, and on the north by the Palo Duro Basin.

Reservoirs: Reservoir rocks consist of porous dolomite, limestone, and sandstone beds that occur in multiple stacked sequences and are frequently associated with anhydrite, salt, and siltstone redbeds. These facies change and intertongue from east to west to prograding of the paleomargin of the shelves into the Midland Basin. Reservoirs are contained in the Pennsylvanian, Strawn, Canyon, and Cisco Formations. Cumulative reservoir thicknesses range up to several hundreds of feet; porosities average 12 percent, and permeabilities average 15 mD. Drilling depths vary from 3,000 to 12,000 ft.

Source rocks: Source rocks for hydrocarbons in Pennsylvanian reservoirs probably include the Late Devonian Woodford Shale and organic-rich bituminous shales of Pennsylvanian age in adjacent basins and indigenous shelf settings.

Timing and migration: The combined structural/stratigraphic traps characterizing this play were formed during Late Pennsylvanian time. Seals are Pennsylvanian shales. Source rocks such as the Woodford Shale should have begun delivering oil from deep basinal settings along migration routes provided by faults and unconformities to reservoirs in Pennsylvanian shelf settings as early as the Permian and oil and gas may still be moving to some of the traps of this play via primary and secondary migration.

Traps: Trapping mechanisms are predominantly a combination of structural and stratigraphic features. Anticlinal and domal structures are areally extensive and of low relief. Combination structural-stratigraphic traps consist frequently of reef sediments and structural noses that wedgeout updip and are associated with lateral depositional and diagenetic facies-change permeability barriers. Multiple stacked porous reservoir rocks are separated by nonproductive impermeable shale, evaporite rocks, and limestone beds that act as effective seals. Discovered hydrocarbons occur at depths of 3,000 to 16,000 ft, with an average of 9,000 ft.

Exploration status: Cumulative production from this play through 1990 was 1.7 BBO, 6 TCFG, and 389 MMBNGL. Jameson, the largest oil field, was discovered in 1946 and has produced 92 MMBO. Indian Basin, discovered in 1962, is the largest gas field with cumulative production of 1.5 TCFG. The first oil field was discovered in 1928 and the

first nonassociated gas was found in 1942. A fair number of oil and gas discoveries have been made in this play in the 1980's.

Resource potential: Prospects for additional small discoveries are deemed to be moderately promising.

4407. UPPER PENNSYLVANIAN AND LOWER PERMIAN SHELF, SLOPE AND BASIN SANDSTONES PLAY

The definitive characteristics of this play are: (1) Late Pennsylvanian reservoirs; (2) quartz sandstone reservoir lithology; and (3) a setting that includes the Val Verde Basin and the Ozona Arch. An encouraging aspect of this play is that a number of discoveries have been made during the 1980's.

The play includes mainly gas accumulations in a combined stratigraphic-structural, stratigraphic, and, to a lesser extent, pure structural traps in clastic and subordinate carbonate reservoirs of primarily Late Pennsylvanian age. The play area is arcuate in shape and covers most of the Southern Delaware and Val Verde Basins.

Reservoirs: Reservoir rocks consist of porous and permeable sandstone with subordinate dolomite and limestone beds. The most important reservoirs occur in clastic sediments of the Pennsylvanian Strawn, Canyon, and Cisco Formations. Canyon Formation reservoirs are sandstone interbedded with shale. Reservoirs are a succession of sandstone beds, 5–10 ft in thickness, scattered through a vertical sequence of 600 ft. Total net pay varies from 20 to 100 ft. Drilling depths vary from 2,000 to 9,000 ft.

Source rocks: The Upper Devonian Woodford Shale in adjacent and subjacent basin settings is a probable source of some of the hydrocarbons in this play. Organic-rich Pennsylvanian and Permian shales are also likely sources for some of the play's hydrocarbons.

Timing and migration: The Pennsylvanian is the time of principal trap formation for this play. The Woodford Shale probably supplied hydrocarbons to newly created traps configured structurally during Pennsylvanian time. All source rocks, including organic-rich Pennsylvanian shales, are probably still active in supplying hydrocarbons to existing traps.

Traps: Trapping mechanisms are predominantly a combination of structural and stratigraphic features. Anticlinal structures are generally associated with lateral facies changes, together with structural nosing and updip lensing. Lenticular sandstone

bodies are numerous. Seals are overlying shale and dense carbonate rocks, updip pinch-outs, and facies-change permeability barriers.

Exploration status: This play's cumulative production through 1990 consists of 262 MMBO, 6 TCFG, and 28 MMBNGL. The play's largest oil field, Todd Deep, was discovered in 1940 and has produced 43 MMBO. Ozona, the largest gas field, was discovered in 1962 and has produced 1.2 TCFG. The first oil discovered in the play dates from 1936 and the first gas from 1946.

Resource potential: The play appears to have reasonably good prospects for additional gas discoveries.

4408. WOLFCAMPIAN CARBONATE, EASTERN AND SOUTHERN MARGINS OF THE CENTRAL BASIN PLATFORM PLAY

The definitive characteristics of this play are its Wolfcampian age, the carbonate composition of its reservoirs, and its setting along the eastern and southern margins of the Central Basin Platform. This play includes 19 oil fields with associated gas. Fields reserves are estimated at 9 MMBO, but the potential for future exploration seems limited by an intensive drilling history.

Reservoirs: Reservoirs include platform-edge carbonate grainstones, wackestones and packstones, and carbonate debris flows on the slopes downdip from the platform edge. Lithology varies from limestone to mixed limestone and dolomite. The reservoirs have individual thicknesses measured in tens of feet and occur in intervals approaching 1,000 ft. Porosities average 10 percent and permeabilities are measured in a few tens of millidarcies. Drilling depths vary from 5,000 to 9,000 ft.

Source rocks: Potential source rocks include the Late Devonian Woodford Shale and organic-rich shales of Pennsylvanian and Permian age in adjacent basin settings.

Timing and migration: The Woodford Shale and organic-rich Pennsylvanian and Permian shales at appropriate depths and temperatures in deep basinal settings have probably supplied hydrocarbons for both primary and secondary migration into Wolfcampian reservoirs from the time that these reservoirs were sealed by indigenous shales until the present day.

Traps: Traps are typically combined structural-stratigraphic features, with primary structural control and porosity variation associated with depositional environments and diagenetic effects playing an important secondary influence on limiting hydrocarbon generation.

Exploration status: Cumulative production of this play through 1990 was 163 MMBO, 248 BCFG, and 25 MMBNGL. The largest oil field, University Block 9 Wolfcamp, has produced 29 MMBO and was discovered in 1953. The first discovery in the play occurred in 1946 at TXL. Most of the play's discoveries were made prior to 1970.

Resource potential: This play has moderate potential for additional hydrocarbon discoveries.

4409. SPRABERRY-DEAN PLAY

The definitive characteristics of this play are: (1) a setting on the floor of the Midland Basin, and (2) mixed silicate and calcareous mudstone, siltstone, and fine sandstone reservoir facies deposited as turbidites in deep-water submarine fans with associated channel systems. Low permeability in the reservoir facies is a major factor limiting the future production potential of this play.

The play includes oil and associated gas fields in a combination of stratigraphic, stratigraphic-structural, and pure structural traps in deep-basinal clastic reservoirs of Lower Permian age. The play area is about 150 mi long, 40–75 mi wide, covers the entire Midland Basin, and is bounded on the west by the Central Basin Platform and on the east by the Eastern Shelf. Maximum thickness of Permian sedimentary rocks is less than 15,000 ft.

Reservoirs: Reservoir rocks consist of laminated sandstone, muddy burrowed sandstone, muddy siltstone and mudstone tongues, which are all intercalated and are poor-quality reservoirs. These sediments were deposited as channel fills, channel-margin bars, and as splay-like distal fans in a deep-water system of submarine fans. Reservoirs are located in the Leonardian Spraberry and Dean Formations and contain over 10 BBO. Individual reservoirs may range up to 200 ft or more in thickness, but porosities (averaging 11 percent) and especially permeabilities (averaging 1 mD) are low. Drilling depths vary from 5,500 to 9,500 ft.

Source rocks: Thin, organic-rich black shale beds are widely distributed in the Spraberry-Dean interval. These shales are interbedded with sandstone and siltstone and generally contain 1-3 percent total organic carbon (TOC). Most of the organic material consists of oil-prone algal and amorphous types, and the shales provide optimum-quality source rocks within the system containing the reservoirs. Hydrocarbon generation from the shale beds probably occurred during Upper Permian

time. Hydrocarbons are believed to have accumulated in the juxtaposed reservoir sandstones during generation.

Timing and migration: Organic-rich shales in the Leonardian Series of this play are generally thought to have provided the oil and gas by short-range migration into low-permeability traps. The 7,000 ft of Permian sedimentary rocks overlying the source section is an insufficient thickness to have resulted in thermal maturation, assuming the existence of the present geothermal gradient during Permian time. It may well be that maturation and migration of the hydrocarbons being recovered from this play didn't start until sometime during the Mesozoic, and it probably continues at the present time.

Traps: Primary trapping mechanisms are stratigraphic, with some associated structural traps, and in combination of the two. Updip thinning and pinch-out of sandstone on the marginal slope of the Eastern Shelf are prevalent. A few simple anticlinal traps also exist, and some fields are contained within a single isolated, elongated sandstone lens. The organic-rich black shales, in addition to being high-quality source rocks, also act as effective seals. Other seals consist of nonporous interbedded shale, dolomitic and impure limestone, and porosity and permeability barriers within the interlaminated reservoir sequences. Trapped hydrocarbons occur at depths of 4,500–9,500 ft, with an average of about 7,500 ft.

Exploration status: Cumulative production through 1990 for this play was 1.08 BBO, 2.77 TCFG, and 419 MMBNGL. The largest oil field is the Spraberry Trend, discovered in 1949, with a production of 452 MMBO and 2.1 TCFG. The first discovery was at Benedum Spraberry in 1947. All major discoveries were made prior to the 1970's.

Resource potential: Potential for additional discoveries in this play is limited by extensive previous drilling.

4410. SAN ANDRES-CLEARFORK, CENTRAL BASIN PLATFORM, AND OZONA ARCH PLAY

The definitive characteristics of this play are: (1) a setting on the Central Basin Platform, (2) dolomitized shallow-water carbonate platform facies with an admixture of silicate sands, and (3) very effective seals provided by evaporite facies. The major drawback for future exploration success of this play is its extensive drilling history.

The play includes oil and subordinate gas accumulations in stratigraphic/structural and structural traps in a platform sequence of carbonate and, to a lesser extent, fine-grained silicate reservoirs of Permian age. The play area is approximately 200 mi long

and 110 mi wide and covers all of the Central Basin Platform and the Ozona Arch; it is bounded on the west and south by the Delaware-Val Verde Basins, and on the east by the Midland Basin. Maximum thickness of Permian sedimentary rocks is less than 10,000 ft.

Reservoirs: Reservoir rocks consist of porous and permeable dolomitized carbonates, limestone and fine-grained sandstone. They include skeletal grainstones, dolomite, limestone, calcareous and silty sandstones, sponge and algal dolomitized limestone, dolomitized mud and wackestone, and vuggy to cavernous carbonate beds. Carbonate rocks were deposited in open to restricted platforms and platform margins associated with sea-level fluctuations, shelf-margin reef development, evaporites, and sabkha deposits. Reservoir quality is enhanced by selective dolomitization, dissolution, fracturing, and leaching. Reservoirs are contained in the Permian Guadalupian San Andres, Grayburg, Queen, Seven Rivers, and Yates Formations; they also occur in the Clear Fork and Wolfcamp Formations. Individual reservoir thicknesses may range up to hundreds of feet; overall porosities average 12 percent and permeabilities average 18 mD. Drilling depths vary from 1,000 to 10,000 ft.

Source rocks: Source rocks include indigenous organic-rich calcareous shale and shaly limestone of Wolfcampian and Leonardian age. Important additional source contributors are the Late Devonian Woodford Shale and organic-rich Pennsylvanian and Permian shales in basins adjacent of the Central Basin Platform. Hydrocarbon generation from adjacent organic-rich source rocks probably occurred during Upper Permian time. Fluids migrated laterally and upward into the present reservoirs.

Timing and migration: The combined stratigraphic/structural traps containing the hydrocarbons of this play were all in existence by the end of Permian Guadalupean time. Mature source rocks were present in the adjacent Delaware, Val Verde, and Midland Basins at this time. It seems likely that these hydrocarbons traveled upward along a combination of faults, unconformities, and permeable stratigraphic horizons into the Permian reservoirs of this play from the time of their inception. Secondary migration into and out of these traps may well continue to the present day.

Traps: Primary trapping mechanisms are generally a combination of structural and stratigraphic features such as anticlinal noses and domes, that are associated with stratigraphic depositional and diagenetic facies changes. Large, simple anticlinal closures also are present. Seals consist of impervious dolomite, shaly carbonate,

anhydrite, and other evaporite facies. Structurally and stratigraphically trapped hydrocarbons occur at depths of 1,000-10,000 ft and average 4,500 ft.

Exploration Status: Through 1990, cumulative production from this play was 11.6 BBO, 26.7 TCFG, and 1.7 BBNGL, making the play the most important producer in the Permian Basin Province. The largest oil field, Yates, discovered in 1926, has produced more than 2 BBO. Eunice Area, discovered in 1929, has produced 850 MBO and 8.8 TCFG. Most of the major discoveries in this play occurred prior to 1950.

Resource potential: Potential for additional discoveries in this play is limited by dense prior drilling.

4411. SAN ANDRES-CLEARFORK, NORTHWESTERN AND EASTERN SHELVES PLAY

The definitive characteristics of this play are (1) a setting on the northwestern and eastern shelves of the Permian Basin Province, and (2) reservoirs consisting primarily of restricted shallow-water carbonate platform sedimentary rocks, with admixtures of silicate clastics and with all of the carbonate rocks dolomitized and all reservoir facies, to a degree, plugged with anhydrite, resulting in relatively low-permeability reservoirs. Extensive drilling and pervasive anhydrite plugging of reservoir facies both serve to limit the prospective future of this play.

The play includes oil and subordinate-gas fields in a combination of stratigraphic, stratigraphic/structural, and structural traps in shelf-margin and interior-facies carbonate and, to a lesser extent, clastic reservoirs of Permian age. The play area covers the whole of the northwestern and eastern shelf area southeast of the Pedernal Uplift and west of the Bend Arch. Maximum thickness of Permian sedimentary rocks in the play is less than 10,000 ft.

Reservoirs: Reservoir rocks consist of porous limestone, dolomite, dolomitized mudstone and wackestone, and lesser amounts of fine-grained clastics frequently associated with evaporites, redbeds and sabkha facies. These rocks appear to have been deposited in platform edge, open-shelf, intertidal, supratidal, and restricted-shelf environments associated with platform growth. Reservoirs are contained in Permian Wolfcampian, Leonardian Clear Fork Formations, and Guadalupian San Andres, Grayburg, Queen, Seven Rivers and Yates Formations. Gross reservoir thicknesses range up to 1,000 ft, porosities average 10 percent, and permeabilities average 6 mD. Drilling depths vary from 300 to 10,000 ft.

Source rocks: Source rocks include indigenous organic-rich calcareous shale and shaly limestone of Permian age; however, it is believed that the Late Devonian Woodford Shale and organic-rich Pennsylvanian and Permian shales in adjacent basins are also important source contributors to the shelf areas. Deposited under restricted shelf, intertidal, and lagoonal environments, the source beds are probably extremely rich in organic material.

Timing and migration: Hydrocarbon generation from adjacent organic-rich source rocks probably occurred during Upper Permian time. Hydrocarbons migrated laterally and upward into the present porous reservoir rocks immediately after generation. The tectonic and depositional structures that control the configuration of the traps of this play were formed by the end of Permian Guadalupean time. The evaporitic seals completing these traps were deposited during the same epoch. It seems likely that mature source rocks as old as the Late Devonian Woodford Shale began delivering oil and gas to migration routes to Permian reservoirs in shelf settings almost immediately after reservoirs were sealed. Subsequently, younger source rocks consisting of organic-rich Pennsylvanian and Permian shales should have contributed additional hydrocarbons to established migration paths, and all undepleted source rocks may still be supplying oil and gas to the reservoirs of this play.

Traps: Primary trapping mechanisms are stratigraphic, structural, and combined stratigraphic/structural. Stratigraphic traps in the shelf sequence are formed by lateral facies changes into nonporous and permeable strata. Structural traps are generally simple anticlinal closures that had topographic relief during the Permian. Buried reef traps are also present. Seals consist of anhydrite, salt beds, nonporous dolomites, and redbeds.

Exploration Status: This play's cumulative production through 1990 was 10 BBO, 7.9 TCFG and 900 MMBNGL. Wasson, the largest oil field, discovered in 1936, has produced 2.4 BBO. Slaughter-Lovelland, also discovered in 1936, is a close second for total oil production with 2.3 BBO. Wasson has also produced 2.2 TCFG and Slaughter-Lovelland has added 1.7 TCFG to the associated gas total. Pecos Slope, the largest nonassociated gas field, was discovered in 1951 and has produced over 300 BCFG. This field's ultimate recoverable gas is judged to exceed 1 TCFG. Major discoveries in this play occurred prior to 1960.

Resource potential: Potential for additional discoveries in this play is limited by dense earlier drilling.

4412. DELAWARE SANDSTONES PLAY

The definitive characteristics of this play are: (1) a setting in the Delaware-Val Verde basins including the flank of the Ozona Arch, and (2) quartz sand reservoirs of Permian age deposited in a predominantly deep-water environment as channel systems in a sequence of turbidite-fan materials. The relatively low permeabilities of the reservoir facies, together with the compacted, thin, and limited extent of individual reservoirs, limits the prospective future of this play.

This arcuate-shape play includes oil and gas fields in combined structural and stratigraphic traps involving anticlines, updip pinch-outs, and channel-fill combination traps in clastic reservoirs of Permian age. The play is confined primarily to the Delaware Basin but, because of similarities, includes shelf-margin sandstone reservoirs in the adjoining Val Verde Basin and Ozona Arch area. Maximum thickness of Upper Permian sedimentary rocks is less than 10,000 ft.

Reservoirs: Major reservoir rocks consist of fine-grained basinal sandstone interbedded with laminated siltstone, organic-rich shale, limestone, and dolomite. In the Ozona Arch area, the reservoirs are open-shelf sandstones. Reservoirs are contained in the Permian Rustler Formation of the Ochoan Series and the Bell Canyon, Yates, Queen, and Cherry Canyon Formations of the Guadalupian Delaware Sands Series. Reservoir thicknesses range up to 50, ft with 20–25 percent porosity and moderate to low permeability. Drilling depths vary from 2,000 to 11,000 ft.

Source rocks: Source rocks are considered to be associated organic-rich basinal shales of Permian age. The relatively low permeability of reservoir rocks suggests that hydrocarbons were generated from sources near the reservoirs and that migration distances were short.

Timing and migration: The mostly stratigraphic traps of this play were formed by the end of Permian Guadalupean time. Because of the relatively low permeability of the play's reservoirs and the juxtaposition of organic-rich shales in the section, it is generally accepted that most of this play's oil and gas has been generated locally and moved into reservoirs via short-range migration. The 6,000 ft of evaporitic overburden covering the source-rock interval would have been insufficient to achieve thermal maturation during Permian time with present geothermal gradients. It may well be that maturation began during the Mesozoic Era. Maturation and migration probably continue to the present time.

Traps: Trapping mechanisms are stratigraphic, primarily updip pinch-outs of channel-fill sandstone bodies in the Delaware Basin. In the Ozona Arch area, anticlinal structure and combined structural/stratigraphic traps are present. Seals are generally impervious silty shales and updip facies changes. Stratigraphically and structurally trapped hydrocarbons occur at depth ranges from 2,000 to 11,000 ft and average about 6,000 ft.

Exploration Status: This play's cumulative production through 1990 was 325 MMBO, 1.6 TCFG and 16 MMBNGL. Geraldine Ford, the largest oil field, was discovered in 1956 and has produced 33 MMBO. The shallow gas pool at Coyanosa, the largest gas accumulation, was discovered in 1962 and has produced 252 BCFG. The first discovery, Wheat, in 1925, has produced 22 MMBO. Most major discoveries have occurred prior to 1970.

Resource potential: This play has moderately good potential for additional discoveries.

UNCONVENTIONAL PLAYS

There are no unconventional plays described in this province report. However, unconventional plays listed in the surrounding provinces may include parts of this province. Individual unconventional plays are usually discussed under the province in which the play is principally located.

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